

Coordination of multiple-power tapping from existing HVDC link

Agha Francis Nnachi, Josiah Munda , Dan Valentine
Nicolae

Department of Electrical Engineering
Tshwane University of Technology
South Africa

nnachiaf@tut.ac.za; MundaJL@tut.ac.za;
NicolaeDV@tut.ac.za

Augustin Mpanda Mabwe

Ecole superieure D'Ingenieurs en Electronique et
Electrotechnique
Amiens, France
mpanda@esice-amiens.fr

Abstract— DC-link transmission of VSC HVDC system has shown to play a vital role for power tapping to serve distributed loads that are near to the link corridor. However, enormous power tapping if not curtailed could have detrimental effect on the main VSCs operation, control and stability. In this paper, single- and multi- power tapping limit determination together with a supervisory optimal control of the power tapping on the dc link of VSC HVDC system is proposed. The effectiveness of the proposed technique is applied to a case study, demonstrated in Matlab/Simulink program and simulation results presented.

Keywords— *power tapping; optimization; HVDC transmission*

I. INTRODUCTION

Connecting the dispersed nature of loads in Africa and generation sources spanning hundreds and in some cases thousands of kilometers have been a serious challenge. Recently, the power utilities in the Southern African Development Community (SADC) countries are seeking to maximize their reserve margins and trade any surpluses of power using transmission systems connecting the large new power sources with the large load systems in compliance with the Southern African Power Pool (SAPP) [1]. One solution to address this challenge is via high voltage direct current (HVDC) transmission.

Ever since the HVDC transmission systems were developed and utilized in power systems, power tapping from these transmission systems to serve isolated communities or loads near the DC-link transmission corridor has been the focus of many researchers and power system planners [2], [3], [4], [5], [6], [7], [8], [9], [10], [11]. However, their research works have assumed tap-off of different percentages of 2%, 5%, 10%, 20% of the main HVDC terminal rating without justification.

In [12], using the principle of uniform loading [13], [14], [15], [16], parallel power tapping limit for a single tapping station from the HVDC link was proposed. In this paper, the work is extended for a multi-power tapping. Here, multi-power tapping limit is derived and to ensure that the sum of the power tapping does not to exceed the multi-tapping limit at any point in time, a supervisory optimal power injection control is proposed. Implementation of this optimization strategy is to be

adopted at a supervisory power tapping control level with the objective of assuring that the total power tapped does not exceed the tapping limit. The optimization procedure defines the control reference corresponding to the allocation of power in each tapping station and allows for the total power tapping not to exceed the limit.

The effectiveness of the proposed technique is applied to a case study, demonstrated in Matlab/Simulink program and simulation results presented.

II. SMALL POWER TAPPING FROM HVDC TRANSMISSION SYSTEMS

A. Requirements of tapping stations

The main requirements for small tapping stations are [17], [2] are reduced fixed cost of tapping station, negligible impact of tapping station on the reliability of the main HVDC system and sufficiently small rating and its control not to interfere with the main HVDC system control i.e. the tap control system has to be strictly local. During power tapping, some of the issues that need strict attention are:

- What effect the power tapping can have on voltage profile especially at high tapping power,
- How to ensure that the power tapped does not upset the main control of the HVDC, and
- Coordination of multiple tapping to ensure that the HVDC does not lose its DC voltage regulation?

B. Tapping methods

Over the years, different methods of using power electronics interface to achieve power tapping from HVDC link have been proposed and studied. Generally, tapping station can be divided into two categories namely series and parallel tapping [18], [19].

1) Series tapping

Figure 1 show a schematic of series tapping stations. The series connected tapping station will cause a voltage drop ΔV_{Tap} and the power tapped can be determined by the following equation:

$$P_{Tap} = \Delta V_{Tap} I_{dc} \quad (1)$$

From (1), it is obvious that the control over the amount of the tapped power is done through the control of the tap voltage. This change in voltage ΔV_{Tap} of the main HVDC system is the major drawback of series tapping. However, because of the negligible impact on the amount of the DC current in the transmission line, it is best suited for small loads with ratings less than 10% of the main HVDC [17], [11].

Series tap-off topology could be a current source based such as reported in [20], [21], [22], [11], [8], [17] or the next generation dc-dc converter based tapping station [10].

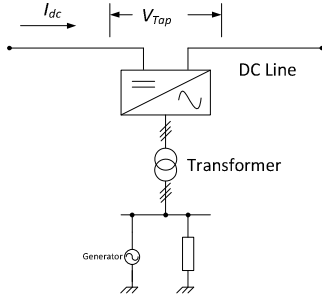


Fig. 1. Schematic of series tapping station

2) Parallel tapping

Figure 2 shows a schematic of parallel tapping station. In this topology, the tapping station with the dc line will cause a reduction in current ΔI_{DC} (I_{Tap}) and power tapped is determined by:

$$P_{Tap} = I_{Tap} V_{dc} \quad (2)$$

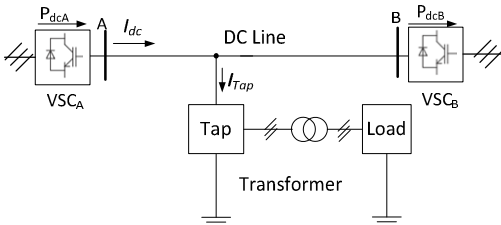


Fig. 2. Schematic of parallel tapping station

The tapping station diverts a fraction of the line's DC current into the local load, and therefore its current rating is determined by the local load's rating. It is evident that the tapped power varies with the DC link voltage of the transmission line. This combination of high voltage and low current rating of load, which will result to high installation cost per kW, bring a limitation in the use of parallel taps for small loads. Therefore parallel tap is most suitable for tapping relatively larger amounts of power (compared with the main terminal's rating), and for the multi-terminal operation of HVDC systems [23]. In [9], a line-commutated topology of parallel tapping was proposed and a voltage source converter tapping station was studied. The prospect of having multiple power tap-offs makes parallel tapping methods economically feasible.

C. Power tapping limit

Equation (3) shows the proposed parallel power tapping limit equation [12], which is a function of the control parameters of the main converter and the DC line.

$$P_{tap_limit} = \Gamma \varepsilon_t \quad (3)$$

where

$$\varepsilon_t = -\frac{U_{dc_min}(U_{dc_min} - U_{dc_ref})}{rx_i} - \frac{x_i}{2L} U_{dcA} I_{dcA};$$

$$\Gamma = \frac{P_{dcA_ref}}{P_{dcA_rated}}$$

P_{tap_limit} = Power tapping limit for a given reference power of the main VSCA control;

ε_t = Power tapping limit of one tapping station for unity reference power of the main VSCA control;

P_{dcA_ref} = the reference power on the main HVDC converter or power flow from VSC_A to VSC_B before the power tapping;

U_{dcmin} = the lower voltage regulation limit in p.u specified in the control;

U_{dcref} = the reference voltage in p.u;

r = resistance per unit length of the line;

x_i = distance of tapping station from bus A;

$rx_i = R_i$;

L = Total length of the DC-link;

U_{dc1} = upper voltage regulation (limit in p.u specified in the rectifier control);

$I_{dc1} = I_{rated}$ = p.u current reference limit (current set point specified in the rectifier control);

P_{dcA_rated} = VSC_A power limit which is a product of U_{dcA} and I_{dcA_rated}

D. Multiple Power tapping limit

Figure 3 shows a schematic of VSC HVDC transmission line with multi-power tapping stations along the DC-link transmission corridor.

If power flows from VSC_A to VSC_B (i.e. the power flows in one direction), then the voltage decreases along the corridor, from VSC_A to VSC_B. Increasing power tapping decreases the voltage along the corridor and could result to voltage collapse. Therefore, multi-power tapping along the corridor should be coordinated to ensure that the system does not lose its voltage regulation resulting to voltage collapse.

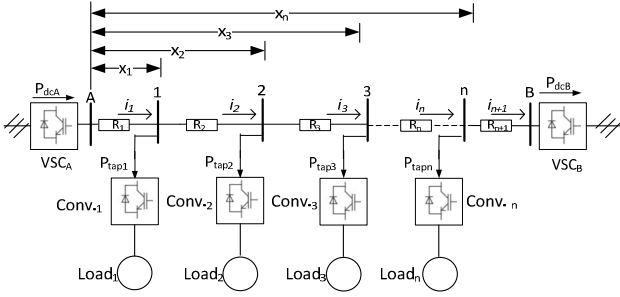


Fig. 3. VSC HVDC with multi-power tapping along the DC-link transmission corridor

When there are multiple power tap-offs, as shown in figure 3, the sum of the power tapped should not exceed multi-power tapping limit. It can be seen that n tap-offs, partition the line into $(n + 1)$ fragments.

The tapping limit for a multiple tap-offs can be determined by considering tap limit at each partition. Considering the first partition between bus A and bus 1, which is $1/(n + 1)$ of the entire length, the tapping limit $P_{tap_1_limit}$ will be

$$\varepsilon_{t1} = \frac{1}{n+1} \left[-\frac{U_{dc_min}(U_{dc_min}-U_{dc_ref})}{rx_1} - \frac{x_1}{2x_1} U_{dcA} I_{dcA} \right] \quad (4)$$

The tapping limit for the second partition bus 1 and 2 will be

$$\varepsilon_{t2} = \frac{1}{n+1} \left[-\frac{U_{dc_min}(U_{dc_min}-U_{dc_ref})}{r(x_1-x_2)} - \frac{(x_1-x_2)}{2(x_1-x_2)} U_{dcA} I_{dcA} \right] \quad (5)$$

Therefore the total power tapping limit on the entire DC-link length (L) for the n tapping stations and for a given P_{dcA_ref} will be

$$P_{multi_tap_limit} = \frac{1}{n+1} \left[-\frac{U_{dc_min}(U_{dc_min}-U_{dc_ref})}{rx_1} - \frac{1}{2} U_{dcA} I_{dcA} + \frac{U_{dc_min}(U_{dc_min}-U_{dc_ref})}{r(x_1-x_2)} - \frac{1}{2} U_{dcA} I_{dcA} + \dots - \frac{U_{dc_min}(U_{dc_min}-U_{dc_ref})}{r(x_n-x_{n-1})} - \frac{1}{2} U_{dcA} I_{dcA} \right] \quad (6)$$

III. OPTIMUM POWER TAPPING ALGORITHM

In order to coordinate the amount of power tapped and ensuring that the multiple power tap-off limit is not exceeded, a supervisory power tapping control (SPTC) is proposed. Figure 4 shows a single line diagram of a two-terminal VSC HVDC link with multiple tapping and SPTC.

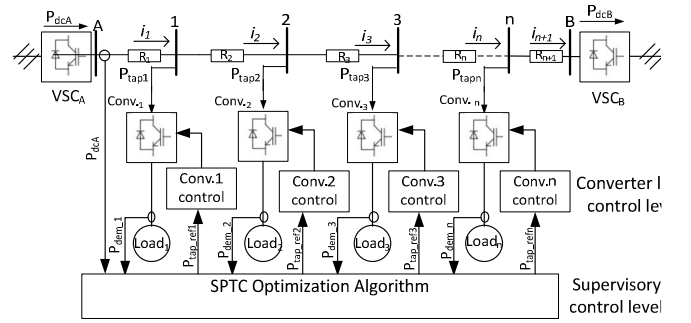


Fig. 4. Single line diagram of two terminal VSC HVDC link with multiple tapping and supervisory power tapping control (SPTC)

This proposed method entails minimisation of the deviation of power tapped ($P_{tapTotal}$) from the multi-power tap limit thereby maximizing the power tapping.

Therefore the objective function is:

$$\text{Min} \left(\sum_{i=1}^n P_{tap_i} - P_{multi_tap_limit} \right)^2 \quad (7)$$

Such that

$$P_{dcA} - P_{dcB} - \sum_{i=1}^n P_{tap_i} - P_{loss} = 0 \quad (8)$$

$$P_{dem_min_i} \leq P_{tap_i} \leq P_{dem_max_i} \quad (9)$$

$$U_{dc_min_i} \leq U_{dc_i} \leq U_{dc_max_i} \quad (10)$$

$$i = 1, 2, \dots, n \quad (11)$$

The equality constraint (8) is the active power balance of the system with line loss $P_{loss} = \sum R_i I_i^2$. The inequality

constraints (9) and (10) are operational limits of the individual tapping stations, where $P_{dem_max_i}$ is the maximum power demand of each tap station. $U_{dc_min_i}$ and $U_{dc_max_i}$ are the limits in the voltage control imposed on all the buses according to the main VSC control settings. This algorithm is implemented using the `fmincon` function [24].

The algorithm mainly consists of two parts. The first part establishes the multi-tap limit. The second part is the constrained nonlinear optimization based on sequential quadratic programming. The objective of this part is to assign appropriate reference power to the respective tap station inverters so that total power tapped does not exceed limit.

IV. SIMULATION

In order to demonstrate the proposed technique, a Matlab/Simulink model of two-terminal VSC HVDC with four tapping stations on the DC-link transmission line is modelled as shown in figure 5. The tapping stations are 190 km from each other. The parameters of Namibia/Zambia Caprivi link VSC HVDC [25], was used for the model with the classical vector control.

The following control setting parameters were used: $U_{dcmin} = 0.94$ p.u.; $U_{dc_ref} = 0.95$; $U_{dcA} = 1.05$ pu; $I_{dcA} = 1$ pu; $r = 0.0139 \Omega/\text{km}$, $P_{dcAref} = 0.63$ p.u., $P_{dcArated} = 1$ p.u. The maximum load demand for the tapping stations are 0.0597 p.u., 0.0529 p.u., 0.0494 p.u., 0.083 p.u. respectively.

With the above main converter control parameters and the power demand of each tapping station as an input to the SPTC, the algorithm calculates multi-tapping limit and assigns respective power references for the tapping station inverter controls.

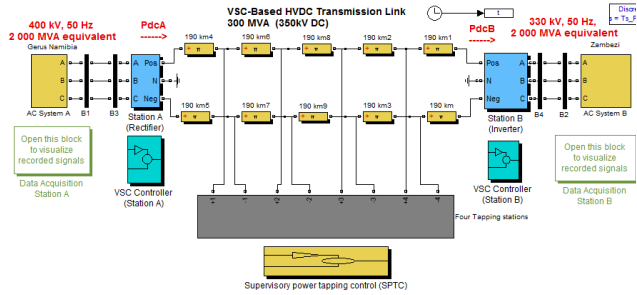
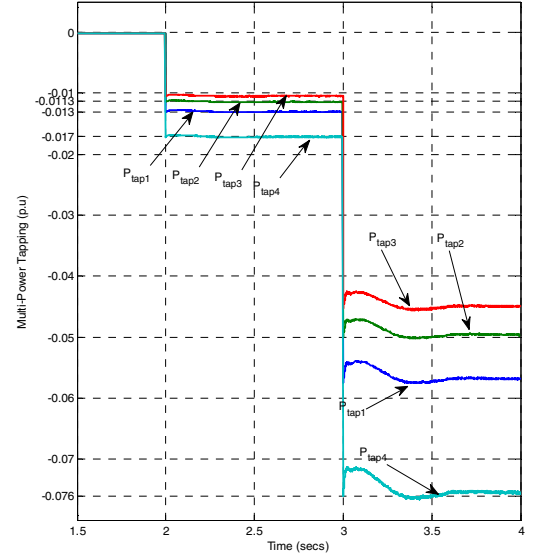


Fig. 5. Matlab/Simulink model of two-terminal VSC HVDC with four power-tapping stations on the DC-link

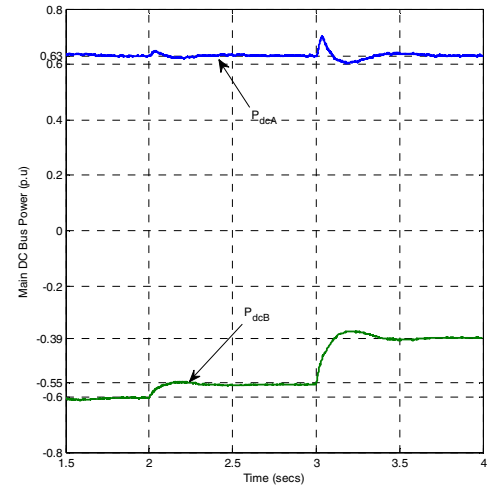
Figure 6 shows the result when the tapping stations are controlled with and without SPTC. From figure 6(a), at 2 secs when the tapping station is switched together with the SPTC, appropriate power tapping was assigned by the SPTC ensuring that the tap limit is not exceeded. At 3 secs, the SPTC is desensitized and the tapping station tapped their respective maximum load demand.

Figure 6(b) shows the response of the main DC bus power depicting oscillation of P_{dcA} when there is no SPTC at 3 secs. Moreover, figure 6(c) shows the DC-bus voltage response and between 2 secs and 3 secs, the DC-bus voltages after minor oscillation, settled at the original steady state bus voltage.

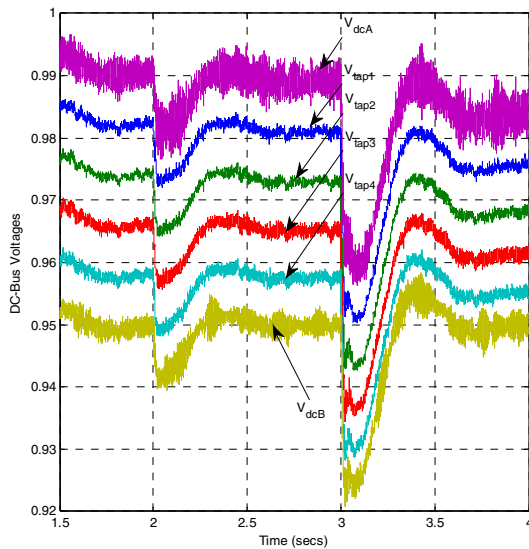
However, at 3 secs when the SPTC was desensitized, the DC-bus voltages dropped substantially due to tapping of power above limit. It can also be noticed that the dynamics of the DC bus voltages were seriously affected and it took almost 0.8 secs before the voltages of the bus settled to steady state.



(a)



(b)



(c)

Fig. 6. System response: (a) Power injection, (b) Main DC-bus power, (c) DC-bus voltages

V. CONCLUSION

In this paper, a multiple power-tap limit on VSC HVDC transmission link is proposed. To ensure that the total power tap-off does not exceed the limit, a supervisory power tapping control algorithm is proposed. Four tapping stations on VSC HVDC link is modelled in Matlab/Simulink to prove the robustness of the algorithm.

REFERENCES

- [1] P. Tuson, "HVDC Strengthening in South Africa," in IEEE PES Power Africa Conference and exposition, Johannesburg, South Africa, 2007.
- [2] N. Ijumba and L. Chetty, "Rural electrification using overhead HVDC transmission lines," *Journal of Energy In Southern Africa*, vol. 23, pp. 45 - 50, 2012.
- [3] L. Chetty, N. Ijumba and A. Britten, "Parallel-Cascaded tapping station," in Proc. of IEEE Int. Conf. Power System Technology, 2004.
- [4] D. Jovicic, "Bidirectional High Power DC Transformer," *IEEE Trans. ON Power Delivery*, vol. 24, no. 4, pp. 2276 - 2283, 2009.
- [5] H. Rahman and B. Khan, "Possibility of Power Tapping from Composite AC-DC Power Transmission Lines," *IEEE Trans. on Power Delivery*, vol. 23, no. 3, pp. 1464 - 1471, 2008.
- [6] B. Collet, J. Taisne, V. Arcidiacono and F. Mazzoldi, "The Corsican Tapping: from design to Commission Test of the third Terminal of the

- Sardinia-Corsica-Ity HVDC Link," *IEEE Tansactions on Power Delivery*, vol. 4, no. 1, pp. 794 - 799, Jan 1989.
- [7] J. Dohahaue, D. Fisher, B. Railing and P. Tatro, "Performance testing of the Sandy Pond HVDC Converter," *IEEE Transactions on Power Delivery*, vol. 8, no. 1, pp. 422 - 428, Jan, 1993.
- [8] M. Bahrman, M. Baker, J. Bowles, R. Bunch, J. Lemay, W. Long, J. McConnach, R. Menzies, J. Reeve and M. Szechtman, "Integration of small taps into (existing) HVDC links," *IEEE Trans. Power Delivery*, vol. 10, pp. 1699 - 1706, 1995.
- [9] D. Jovicic and B. Ooi, "Tapping on HVDC lines using DC transformers," *J Electric power system research*, vol. 81, pp. 561 - 569, 2011.
- [10] A. Mauricio, P. Carlos and C. Felipe, "A 25-MW Soft-Switching HVDC Tap for 500-kV Transmission Lines," *IEEE T Power Delivery*, vol. 19, pp. 1835 - 1842, 2004.
- [11] A. Ekstrom and P. Lamell, "HVDC tapping station: power tapping from a DC transmission line to a local AC network," *IEEE 1991 International conference on Power, Energy, & Industry Applications*, pp. 126 - 131, 17 - 20 Sept 1991.
- [12] "Small power tapping limit on dc-link of VSC HVDC," in *IECON 2013 - The 39 th Annual Conference of the IEEE Industrial Electronics Society*, Vienna, Austria, 2013.
- [13] B. Arijit, m. Arindam, H. Mark and S. E. Joe, "Determination of allowable penetration levels of distributed generation resources based on harmonic limit considerations," in *IEEE Transactions on power delivery*, 2003.
- [14] M. N. Bandyopadhyay, *Electrical power systems: theory and practice*, PHI Learning Pvt. Ltd., 2006.
- [15] C. L. Wadhwa, *Generation, Distribution and Utilization of Electrical Energy*, New Age International, 1989.
- [16] S. N. Singh, *Power generation: transmission and distribution*, 2008.
- [17] E. M. Agha and R. Menzies, "Application of modern power electronics in power tapping from HVDC transmission systems," in *WESCANEX 95. Communication, Power and Computing. Conference Proceedings*, IEEE, 15-16 May 1995.
- [18] D. V. Nicolae, A. A. Jimoh and J. Van Rensburg, "DC current Source to Voltage CT-Based Converter," in *International Aegean Conference on Electrical Machines and Power Electronics*, Sept 2007.
- [19] M. Aredes, C. Portela, A. Aquino and C. Peixoto, "A 500 kV Soft-Switching HVDC Tap". *Cigre* 14-115.
- [20] E. Lamm, Uhlmann and P. Danfors, "Some aspects of tapping of HVDC transmission systems Direct current," may 1963.
- [21] J. Bowles, H. Nakra and A. Turner, "A small series tap on an HVDC line," *IEEE Trans. Power App. Syst.*, Vols. PAS - 100, pp. 857 - 862, 1981.
- [22] H. Turanli, R. Menzies and D. Woodford, "A forced commutated Inverter as a small tap on a DC line," *IEEE Transactions on Power Electronics*, vol. 4, no. 2, pp. 187 - 193, 1989.
- [23] IEEE-PES Task Force on Small HVDC Taps, "Integration of small taps into (existing) HVDC Links," *IEEE Transactions on Power Delivery*, vol. 10, no. 3, pp. 1699 - 1707, July 1995.
- [24] MATLAB, Optimization tool box User's guide, Apple Hill Drive Natic: The MathWorks, Inc, 2014.
- [25] T. G. Magg, M. Machen, E. Krige, H. D. Mutschler and J. Waborg, "Caprivi Link HVDC Interconnector: The first VSC HVDC power transmission with overhead lines," in *CIGRE SCB4 Meeting and Colloquium*, 21, rue d'Artois, F-75008 PARIS, October 2011.